REPORT No. 89

COMPARISON OF ALCOGAS AVIATION FUEL WITH EXPORT AVIATION GASOLINE

By V. R. GAGE, S. W. SPARROW, and D. R. HARPER, 3d
Bureau of Standards

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RÉSUMÉ.

This report was prepared for the National Advisory Committee for Aeronautics and describes an investigation conducted for the Navy Department at the altitude laboratory at the Bureau of Standards and its publication is authorized by the Navy Department.

Mixtures of gasoline and alcohol when used in internal-combustion engines designed for gasoline have been found to possess the advantage of alcohol in withstanding high compression without "knock," while retaining advantages of gasoline with regard to starting characteristics. Tests of such fuels for maximum power producing ability and fuel economy at various rates of consumption are thus of practical importance, with especial reference to high-compression engine development.

Aviation alcogas, prepared by the Industrial Alcohol Co., of Baltimore, Md., for trial by the Navy Department and by the latter submitted to the Bureau of Standards for test, was a mixture apparently of about 40 per cent alcohol, 35 per cent gasoline, 17 per cent benzol, and 8 per cent other ingredients. This is not the alcogas prepared for commercial or passenger car use. The exact composition and methods of manufacture are a trade secret.

The tests made for the Navy Department consisted in a direct comparison, in a 12-cylinder Liberty engine, between alcogas and standard "X" (export grade)[1] aviation gasoline with respect to maximum power attainable, and fuel consumption with the leanest mixture giving maximum power. The tests were made in the altitude laboratory at the Bureau of Standards, where controlled conditions simulate those of any altitude up to 30,000 feet. The speed range covered was from 1,400 to 1,800 revolutions per minute and the altitude range from ground level to 25,000 feet. Two series of comparisons were made, one with 5.6 compression ratio pistons and one with 7.2 compression ratio pistons.

The results of the tests showed the following performance of alcogas in comparison with X gasoline as a standard:

(1) At 5.6 compression the same maximum power production at ground level and a general average of 4 per cent more power at altitude, the maximum difference being about 6 per cent at 6,400 feet and 1,800 revolutions per minute.

(2) At 7.2 compression an average and fairly uniform increase of 4 per cent in power at altitude, no comparative figure for X gasoline at ground level being determined with this compression.

(3) A fuel consumption per brake horsepower of from 10 per cent to 15 per cent more by weight to secure this maximum power at any altitude or speed with either compression ratio. Owing to 12 per cent higher density of alcogas, the fuel consumption in terms of volume per brake horsepower is practically the same as with X gasoline.

(4) Thermal efficiency superior by about 15 per cent. A pound of alcogas contains about 22 per cent less heat units than a pound of gasoline, so that in securing more power with 15 per cent greater weight of fuel it is evident that the available energy of alcogas is more fully utilized than that of gasoline.

Considering the high rate of fuel consumption by weight for alcogas in regard to its effect on plane operation it is to be borne in mind that the weight of fuel is usually about one-seventh that of the total plane weight, so that a 15 per cent greater fuel supply is only a 2 per cent increase in the total weight to be lifted and propelled. This is more than compensated by the

[1] Meeting specification of 1917 for the aviation gasoline shipped abroad for the A. E. F.

5 per cent increase in power obtainable. The necessity of greater fuel supply, by weight, of alcogas in comparison to gasoline for a given mileage does not entail the sacrifice of any additional space, as the density of alcogas is 12 per cent greater than that of gasoline.

Since a 7.2 compression ratio is generally considered too high for gasoline, a comparison is desired of the changes of brake horsepower, fuel consumption, and required radiator capacity (ratio of jacket heat loss to brake horsepower) between alcogas at this compression and X gasoline at 5.6 compression. This comparison shows that alcogas with 7.2 compression develops about 15 per cent greater power with the same weight of fuel per unit power. The radiator capacity required per brake horsepower remains the same.

There is no tangible way of comparing "smoothness" of operation of an engine, but the testing staff expressed the opinion that at all times the alcogas gave a smoother running engine than did X gasoline. The use of the fuel was not continued over an interval sufficiently long to give any data in regard to the effect on the engine of continued operation.

OBJECT OF TEST.

This report is a record of a direct comparison of performance of alcogas aviation fuel and standard X (export grade) aviation gasoline in a 12-cylinder Liberty engine. The comparison was made at the request of the Navy Department to determine the relative merits of the two fuels for aviation use, with particular reference to use in extremely high compression engines. Comparison was therefore made at 7.2 compression ratio, as well as at 5.6 compression ratio (about the common ratio in aviation engines of the present date). The measurements made were brake horsepower and fuel consumption for maximum power.

DESCRIPTION OF FUELS.

The physical properties of the two fuels used in these tests are given in Table I and figure I. The distillation figures were determined by the Bureau of Mines method, as described in their Technical Paper No. 214 (Motor Gasoline, Properties, Laboratory Methods of Testing, and Practical Specifications).

The gasoline was the standard reference fuel of this laboratory ("X" gasoline), prepared for the Bureau of Standards by the Atlantic Refining Co. from Pennsylvania crude oil. It complies with Specification No. 3512 of the Bureau of Aircraft Production for export aviation gasoline for the use of the American Expeditionary Forces, 1918.

TABLE I.—*Distillation and other properties of alcogas and X gasoline.*

	Aviation alcogas.	X gasoline.
Heating value (total):		
British thermal units per pound	15,910	20,340.
Calories per gram	8,840	11,300.
Appearance	Clear lavender	Clear water white.
Odor	Alcohol and ether	Gasoline.
Specific gravity at 15.6° C.	0.799	0.710.
Distillation:		
Initial boiling point	60° C.	59° C.
10 per cent	65° C.	72° C.
20 per cent	67° C.	77° C.
30 per cent	69° C.	82° C.
40 per cent	71° C.	87° C.
50 per cent	73° C.	92° C.
60 per cent	74° C.	97° C.
70 per cent	76° C.	103° C.
80 per cent	78° C.	111° C.
90 per cent	145° C.	127° C.
95 per cent	177° C.	150° C.
Dry point	184° C. (97 per cent)	153° C. (96 per cent).
Residue, per cent	1	1.5.
Loss, per cent	2	2.5.
Reaction to litmus	[illegible] acid	
Corrosion	[illegible] eposit	
Gum, per cent	0.02	

The alcogas fuel was prepared by the Industrial Alcohol Co. of America, Baltimore, Md., for aviation use. It was not the same mixture as that prepared for commercial or for passenger car use. Although the composition and methods of manufacture are a trade secret, it is probable that the composition of the aviation alcogas used in these tests was about 40 per cent alcohol, 35 per cent gasoline, 17 per cent benzol, 8 per cent toluol, ether, etc. Since commercial alcohol and gasoline are not readily miscible, it is necessary to add some ingredient, such as benzol, to secure homogeneity and another must be added to lower the freezing point. Alcogas is a mixture somewhat similar to the Taylor fuel, 33 per cent alcohol, 40 per cent gasoline, 27 per cent benzol, tested by the Bureau of Mines in experimental aviation engines and found capable of withstanding a compression of 8.2 without knock. It is this characteristic which makes mixtures of this type worthy of special study as engine fuel.

DESCRIPTION OF TEST PLANT.

The tests were made in the altitude chamber at the Bureau of Standards, which is designed to give conditions of pressure and temperature such as may be found at any altitude from ground to 30,000 feet. An air pump reduces the pressure in the chamber and in the engine exhaust piping. A refrigerating equipment, together with electric heating coils, give ready control of the temperature conditions at the engine. All controls and measuring devices are located outside of the chamber. A detailed description of the altitude chamber is given in Report No. 44 of the National Advisory Committee for Aeronautics.

A Liberty 12-cylinder aviation engine was used, manufacturers' No. 323, rebuilt at the Bureau of Standards. The oil used was Mobile B. When running with the regular 5.6 compression ratio the engine was standard except that it was equipped with two Stromberg 2-inch duplex carbureters, permitting extreme latitude in the adjustment of air to fuel ratio of the mixture supplied to the engine. Special pistons were fitted to give the 7.2 compression ratio. In each case, the clearance volume was determined by filling the compression space with oil. The compression pressures were measured with a check valve and gage. With the 5.6 compression ratio at 900 revolutions per minute, the compression pressure was about 125 pounds per square inch. With a 7.2 compression ratio, at the same speed, it was about 170 pounds per square inch.

Fuel consumption was measured by direct weighing, noting the time to consume a predetermined weight of fuel. The laboratory is equipped with two fuel tanks, each on a platform scale, and a valve in the intake supply line of the carbureter shifts the supply from one tank to the other.

DESCRIPTION OF TEST PROCEDURE.

These tests were made for the specific purpose of comparing alcogas to X gasoline as an aviation fuel; nevertheless many observations were made that have only indirect bearing upon the fuel comparison, but which, in connection with similar data from other tests, may lead to a more complete understanding of the many factors entering into the various problems connected with internal combustion engines.

The manner of conducting the tests was, briefly, as follows: The engine was started on one of the fuels, and the air, load, speed, oil, jacket, etc., conditions adjusted. Starting with a mixture known to be rich, the fuel supply was gradually reduced and the maximum torque noted, the leaning of the mixture being continued until the torque was appreciably below its maximum value; then the fuel flow was increased only enough to again obtain the maximum torque. All the data in this test were secured with engine throttles wide open. When conditions and adjustments were as desired, observations were made of the speed, load, various pressures and temperatures and quantities, while the time required to use a certain weight of the fuel was noted. At the end of the run on one of the fuels the valves were turned so as to supply the engine with the other fuel. After sufficient time to be sure that none of the previous fuel remained in the line unused, the carbureter was again adjusted for maximum torque with minimum fuel, in the manner described above. By following this procedure there was very little chance for any change of engine condition to enter into the comparative results from the two fuels. After the tests with ordinary (5.6) compression ratio, the engine was taken down, the special 7.2 compression pistons were put in, the engine was thoroughly cleaned, overhauled and some replacements of parts made. This overhaul had no influence on the comparison of the two fuels with either one of the compression ratios, all such comparative runs being made according to the procedure just described, which eliminates engine changes. Other comparisons such as that of the engine performance under different compression ratios, may be affected to some slight degree by the overhaul, and deductions from such data will not have quite as high a degree of accuracy as they would from a test conducted with primary attention to constancy of engine conditions. This fact should be borne in mind in examining figures 24, 25, 26, and 27, although it should not be inferred that these curves fail to merit reasonable confidence.

RESULTS OF TEST.

The test data have been summarized in the curves forming figures 2 to 27. The first group, figures 2 to 12, include the data obtained with the higher or 7.2 compression ratio pistons. Figures 13 to 23 include the lower of 5.6 compression ratio results. Figures 24 and 25 compare the two compression ratios, with either fuel (fig. 24, alcogas, and fig. 25, X gasoline) as to effect on power, thermal efficiency, and fuel consumption. Figures 26 and 27 are a comparison of alcogas at 7.2 compression raio and X gasoline at 5.6 compression ratio, in regard to brake horsepower, pounds of fuel per brake horsepower hour, and heat lost to jacket per brake horsepower.

On figure 2 and figure 13 are plotted brake mean effective pressures versus revolutions per minute. The points are computed directly from observed data. The faired curves are used as the basis of the curves shown in figures 3 and 14, brake horsepower versus revolutions per minute on which the points shown were computed directly from test data, without previous averaging in any respect.

The fuel consumption is shown on figures 4 and 15 in total weight consumed per hour, and on figures 5 and 16, in pounds per brake horsepower hour. The first named curves have been used as an aid in judging engine performance and as a check on other curves. They do not contribute the basis of the second set, which are faired from points computed directly from the original data. In locating faired curves less weight is given to those observation points which the notes made during test show may have been subject to uncertainties of engine behavior.

The scattering of the points on figures 5 and 15 indicate inconsistencies in fuel consumption data rather out of proportion to the exactness with which the power and other measurements could readily be made. This may be attributed to a certain slowness in response of the engine when changes of mixture were made, a sluggishness distinctly less in evidence at 7.2 compression than at 5.6 compression.

Even under the most favorable conditions, considerable change in mixture is possible for a very slight change in power, so that great accuracy is not possible in duplicating the condition of minimum fuel for maximum power. This, not lack of precision in measuring the fuel, is the explanation for the scattering of the points on figures 5 and 16. It was observed that with the 7.2 compression less change of mixture was required to produce a noticeable change in power than with the 5.6 compression. Consistency in fuel consumption data could have been secured had a single arbitrary carburetor adjustment been chosen and used for each fuel, but then the results would have been of no value for the object of these tests. It was desired to find the best performance of the engine with each fuel, absolutely independent of the characteristics of the carburetor. Incidentally, the weight of air used was also determined, so that the data can be used to obtain information as to what the carburetor characteristics should be, for all conditions existing in these tests. The values of thermal efficiency and fuel consumption per unit power, figures 24 and 25, both include factors dependent upon the carburetor adjustment, and are subject to a possible error of about 2 per cent for this reason, even though the actual data were obtained with greater precision.

Measurements of pressure and temperature in intake and exhaust manifolds, valve conditions, etc., give qualitative indications in regard to richness of mixture, and these incidental test data afford a slight assistance in locating the faired curves of figures 5 and 16, by indicating relative weight to be given to scattered points. No attempt has been made, however, to apply hypothetical corrections for unknown conditions, and the points are as observed.

The faired curves of figures 5 and 16, fuel consumption per unit power versus speed are used as a basis for the plot in the other coordinate, fuel consumption per unit power versus altitude in figures 6 and 17.

The heat balance, or record of relative utilization of the heat supplied by the fuels, is shown on figures 7 to 10 and figures 18 to 21. Four partitions of energy are diagrammed, namely (1) the percentage measured as appearing in brake horsepower, (2) that discharged as heat in exhaust gases, (3) that absorbed in the jacket cooling water, and (4) the residual or difference between the sum of the three foregoing percentages and 100 per cent. The residual heat is in reality greater than this value because of the unmeasured heat obtained from combustion of the lubricating oil. The fuel which escapes unburned in the exhaust gases is accounted for in the "residual" values, the exhaust losses including only the sensible heat of the gases and the latent heat of the water vapor. The points shown are computed directly from test data. There being no data on "residual" heat, these curves are located from the faired curves of the other three plots, rather than from points computed as residual to the observation points at the basis of these plots.

Although the curves of heat balance are plotted against speed as abscissæ, no significance attaches to the slope as rate of change of heat distribution with change of speed. For example, no inferences from figures 18 and 19 that brake horsepower, jacket and exhaust heats certainly ncrease with speed at 1,250 feet altitude and decrease at 6,400 feet altitude would be justifiable; there being many variables (including the air to fuel ratio) which affect heat distribution quite independent of speed, and which may have conspired accidently to slope one set of curves up and the other down. What the curves do show is the relative situation as regards the two fuels, and the general magnitude for both at any particular speed.

The curves indicate a pronounced difference in the two fuels, as regards heat appearing in the exhaust gases and in the residual group. When using alcogas, a greater percentage of the heat supplied appeared in the exhaust, more was converted to useful work, and less wasted unburnt (part of the residual), than when using X gasoline.

Selecting the normal engine speeds of 1,600 revolutions per minute and 1,700 revolutions per minute, the heat balance curves of figures 7 to 10 and 18 to 21 are recast into plots of heat balance versus altitude, figures 11 and 22. The curves correspond exactly to the faired curves of the parent set, rather than the estimated smoothest curve through the points, which are computed directly from observed data, and it will be noted that they match remarkably closely.

The slope of the curves should be interpreted with the same degree of reservation noted above for the companion set of curves, nevertheless it seems justifiable to accept the reverse curvature, which is rather marked, as a real reversal with altitude and not a mere accidental coincidence of some undetermined cause depressing or raising values. This conclusion is partly from results of other tests (with different fuels) where in numerous instances evidence has appeared that most complete combustion of gasoline is secured at conditions corresponding to the altitude of 10,000 to 15,000 feet.

In figures 12 and 23 (compression ratios 7.2 and 5.6, respectively) are summarized the differences between the engine performance of the two fuels. The performance of X gasoline is used as the reference zero in each case, and the percentage increase or decrease obtained with alcogas, as shown by the faired curves of the preceding figures, is plotted. Comparison is made of brake horsepower, fuel consumption per brake horsepower, and thermal efficiency at all speeds and altitudes of the test.

The curves of figures 24, 25, 26, and 27, relating to engine performance rather than directly to fuel comparison, have been discussed in the closing paragraph of the section entitled "Description of test procedure."

CONCLUSIONS.

Brake horsepower. (Figs. 12 and 23).—The alcogas shows a better maximum power-producing ability than X gasoline at all speeds and altitudes, except at ground, the maximum difference being 6 per cent. At ground level the two fuels gave the same result at 5.6 compression, while at 7.2 compression comparison was omitted because of the tendency of gasoline to knock at such high compression. The most common difference, omitting the extremely high and low speeds and considering all altitudes, is about 4 per cent, which may be accepted as the figure for superiority in brake horsepower of alcogas over X gasoline.

Fuel consumption.—The gain in power-producing ability noted above for alcogas is at the expense of considerable increase in fuel consumption. Figure 12 shows differences reaching 20 per cent. The general average is an excess consumption, per brake horsepower, of alcogas exceeding 10 per cent (by weight) at 5.6 compression ratio and nearly 15 per cent at 7.2 compression ratio. (Comparison by volume is noted below.)

Thermal efficiency.—Alcogas shows about 15 per cent higher thermal efficiency than gasoline. This figure, as a general average, is taken from figures 12 and 23. Stated in terms of brake thermal efficiency of an engine, 15 per cent superiority of alcogas over gasoline means that if an engine using gasoline is 25 per cent efficient, it would be 28 to 29 per cent efficient on alcogas.

Comparisons of alcogas and X gasoline by volume.—Alcogas is 12 per cent more dense than gasoline; consequently all the above figures are very different when comparison is made on the basis of the pint or gallon as a unit instead of the pound. The maximum brake horsepower attainable is independent of this unit, so that the figure is 4 per cent, as before. The excess fuel consumption per brake horsepower of 10 to 15 per cent by weight becomes practically zero on the volume basis. The total heating value per gallon of alcogas is about 106,000 British thermal units and of gasoline 120,000 British thermal units, a difference of 12 per cent referred to gasoline as a base, instead of 22 per cent difference as by weight. This figure is seen to be of the same order of magnitude as the difference in thermal efficiencies of the fuels. Computing the effective useful work obtainable (product of British thermal units supplied and thermal efficiency) it is found to be the same from a gallon of either alcogas or gasoline.

General engine performance.—While there is no tangible method of comparing the "smoothness" of operation of the engine, the testing staff felt that alcogas gave a "smoother" running engine at all times than did the X gasoline. No tests were made to determine the condition of the engine after continued use of alcogas fuel, but no evidence was found of any evil effects.

Apparently the change in compression ratio has about the same effect, no matter which of the two fuels is used, until the temperature and pressure conditions are such as to cause poor engine operation with gasoline. The main advantage of alcogas seems to be that it is known to be free from tendency to knock on ground level when using the 7.2 compression with wide-open throttle.

The numerical values for effect of changing compression ratio, figures 24, 25, 26, and 27 are subject to an undetermined uncertainty, because of the overhauling of the engine (see section on test procedure), but it is probable that this uncertainty is small and that it is safe to state that the increase of brake horsepower at 7.2 compression over that at 5.6 compression averages at least 10 per cent for all speeds and altitudes, and that the fuel economy for maximum power is improved, so that the fuel consumption per brake horsepower and the thermal efficiency are at least 10 per cent better with the higher compression. It may be of interest to note that the "air-standard efficiency" (based on an ideal engine following Otto cycle) increases about 10 per cent upon raising the compression ratio of the Liberty 12-cylinder aviation engine from 5.6 to 7.2 results in about the expected change in efficiency, power, etc.

It is generally considered that a 7.2 compression is too high for gasoline fuel. Therefore it is of interest to compare the engine performance using gasoline with the 5.6 compression with performance when using alcogas with 7.2 compression. A general comparison of the change of brake horsepower, fuel consumption, and required radiator capacity (ratio of jacket heat loss to brake horsepower) under these conditions is given on figures 26 and 27. Alcogas with the 7.2 compression pistons gives a general average of about 15 per cent more power than X gasoline with the 5.6 compression pistons. The pounds of fuel per unit power is about the same, perhaps favoring slightly the use of alcogas with the higher compression. Figure 27, comparing the ratio of heat in jacket water to power, shows this ratio to be the same, but as the power obtained from alcogas in a 7.2 compression engine is greater, more radiator capacity would be required than when using X gasoline in a 5.6 compression engine.

NOVEMBER 25, 1919.

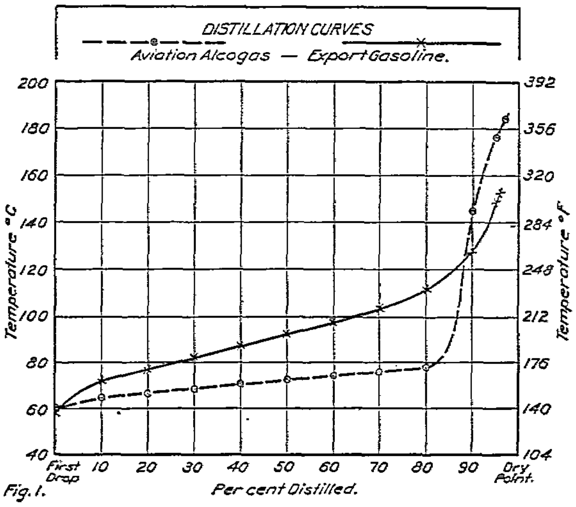

Fig. 1.

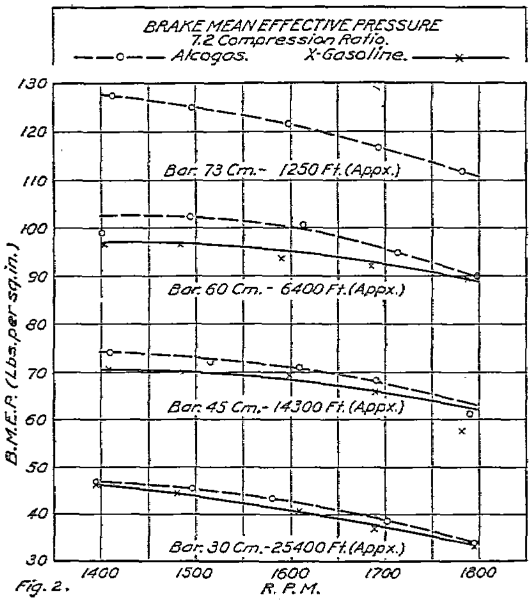

Fig. 2.

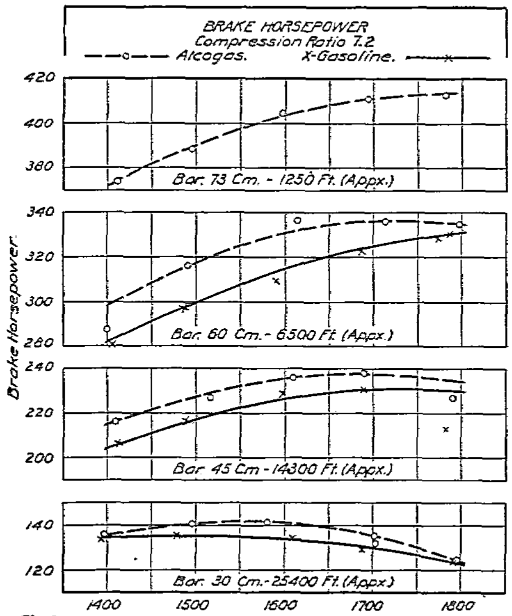

Fig. 3.

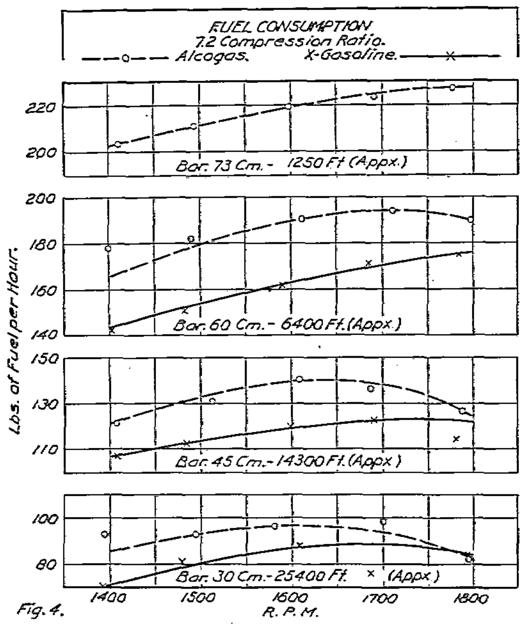

Fig. 4.

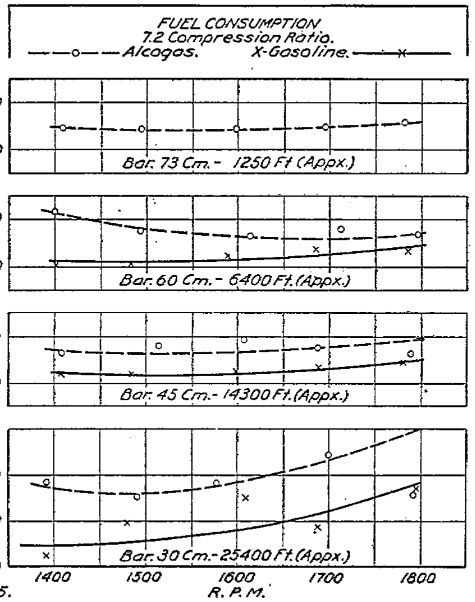

Fig. 5.

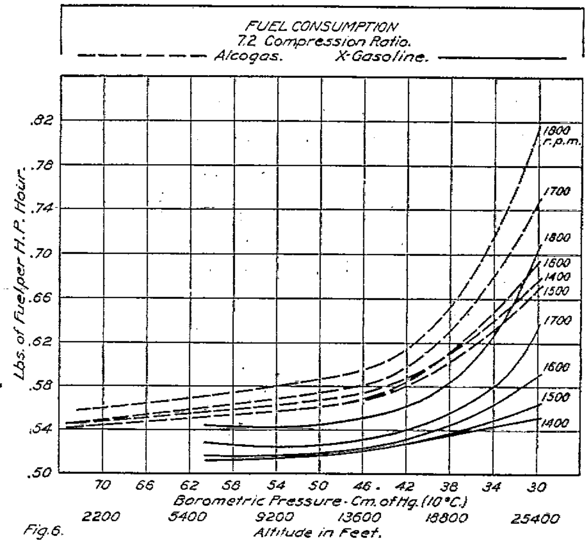

Fig. 6.

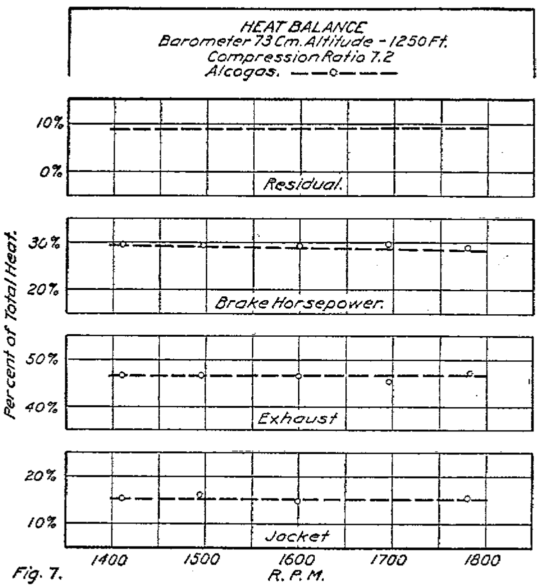

Fig. 7.

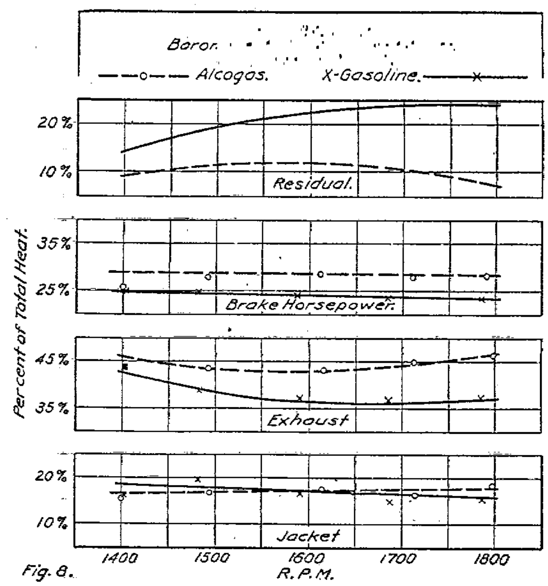

Fig. 8.

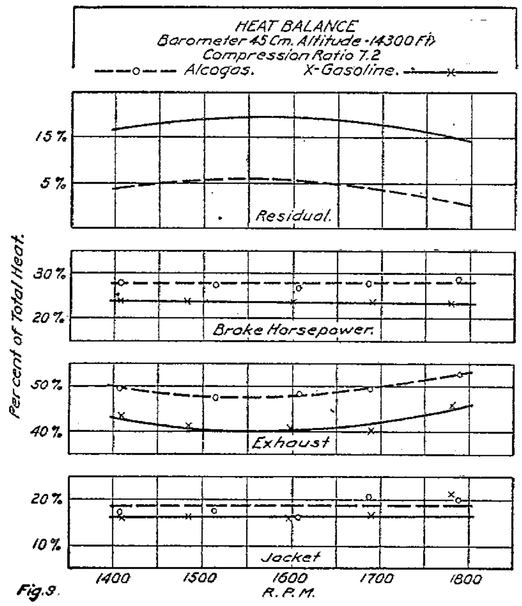

Fig. 9.

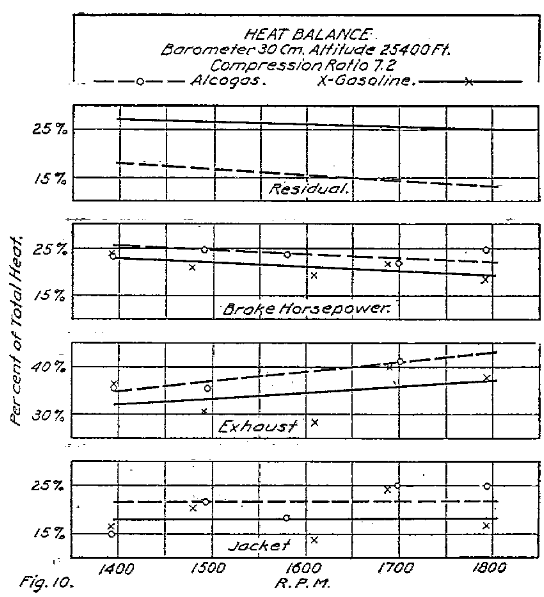

Fig. 10.

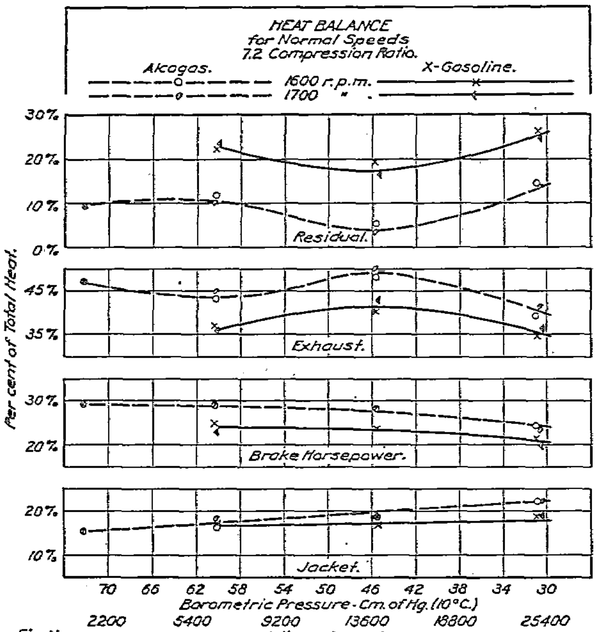

Fig. 11.

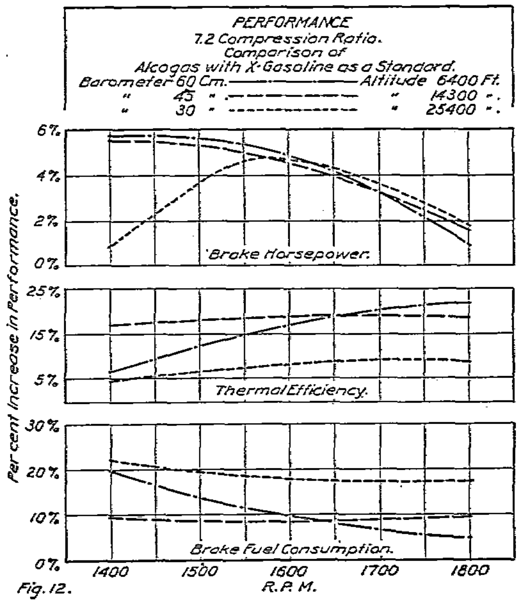

Fig. 12.

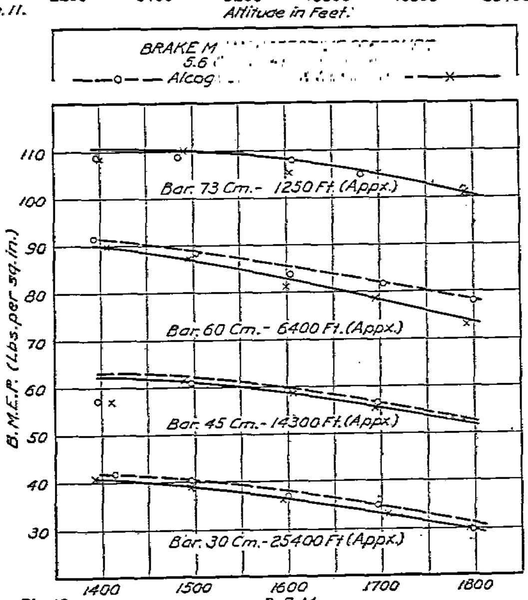

Fig. 13.

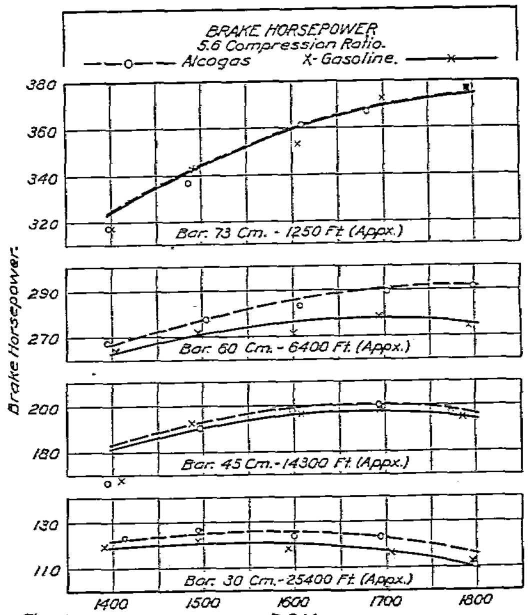

Fig. 14.

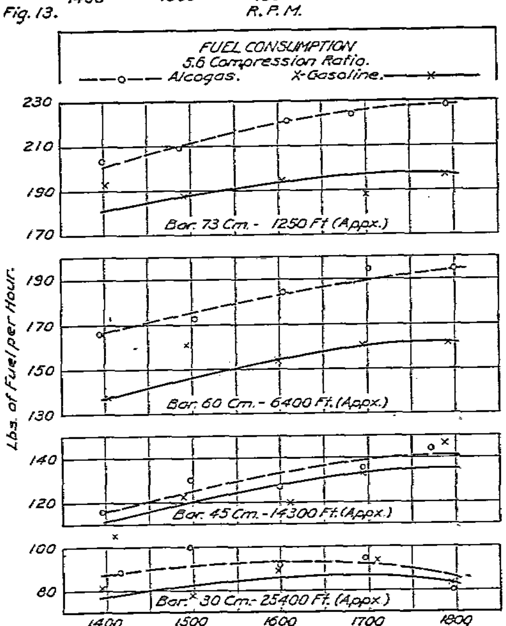

Fig. 15.

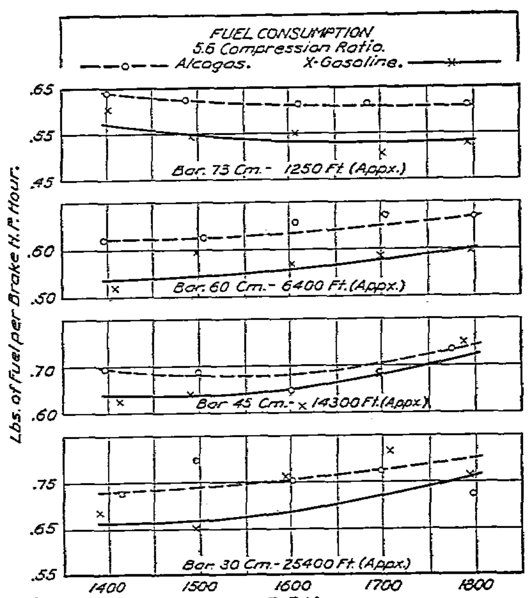

Fig. 16.

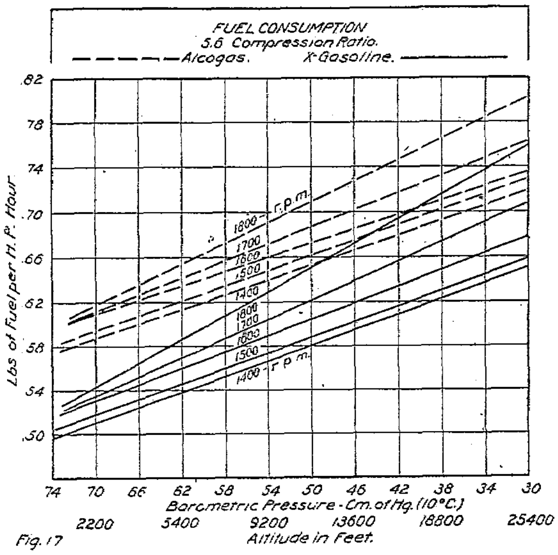

Fig. 17

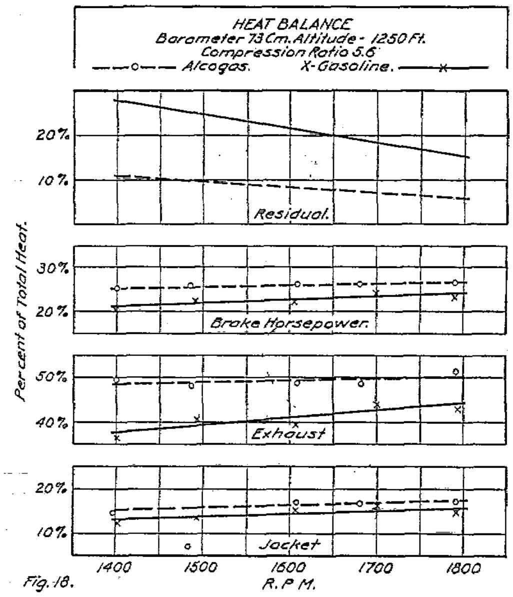

Fig. 18.

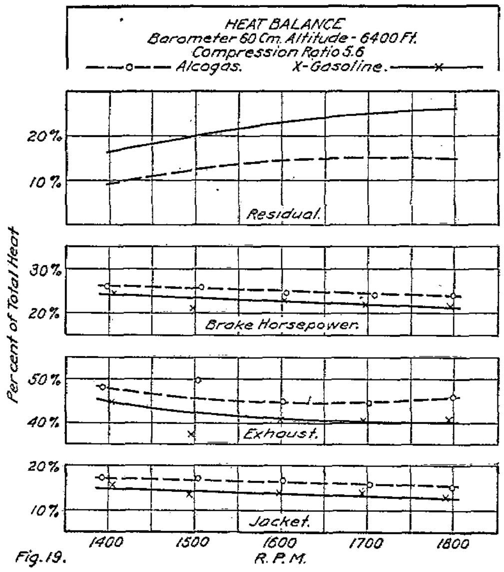

Fig. 19.

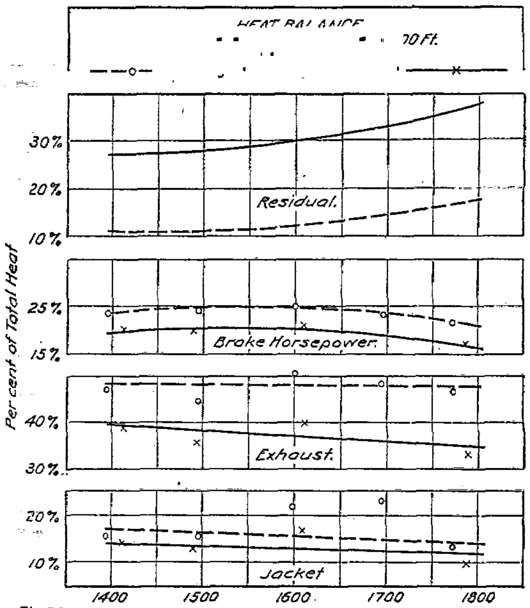

Fig. 20.

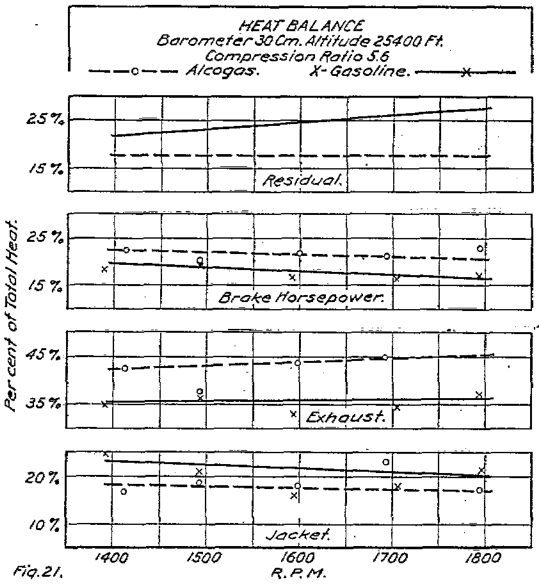

Fig. 21.

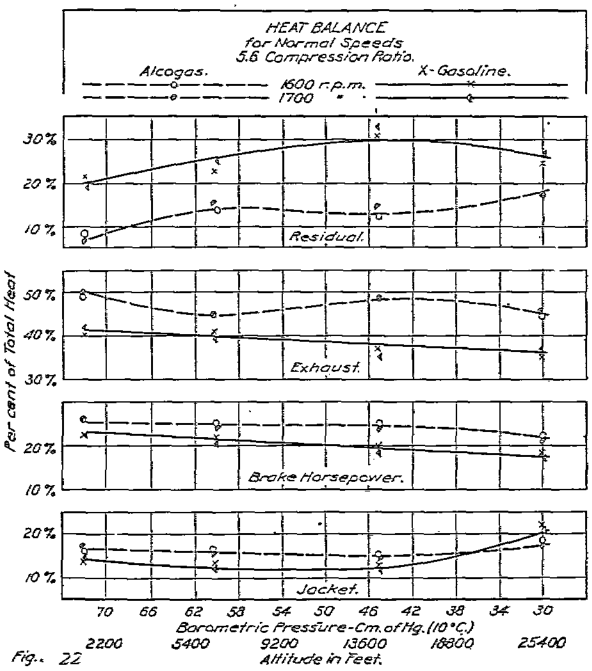

Fig. 22

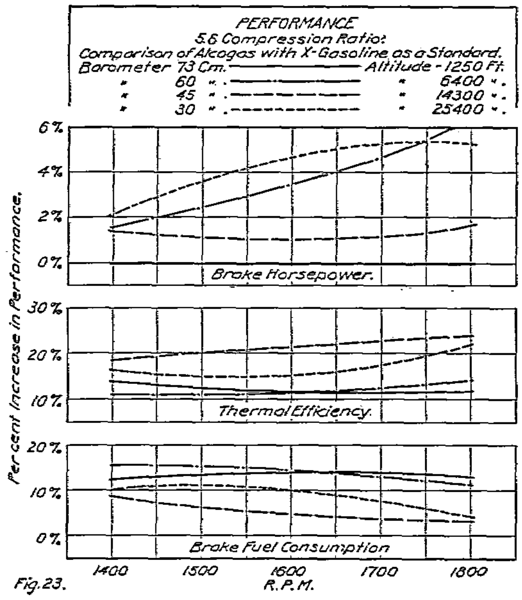

Fig. 23.

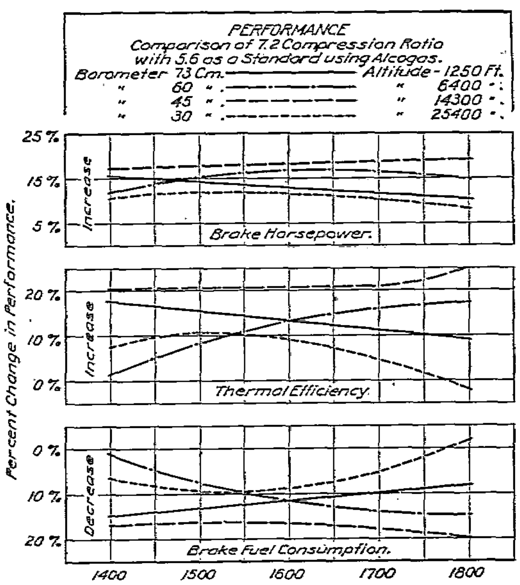

Fig. 24.

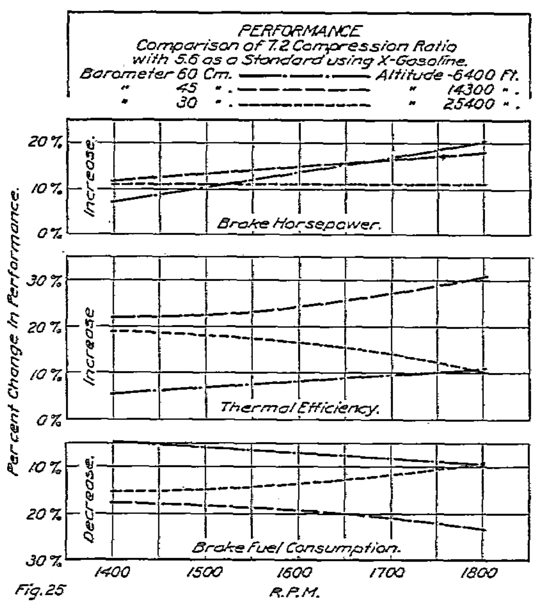

Fig. 25

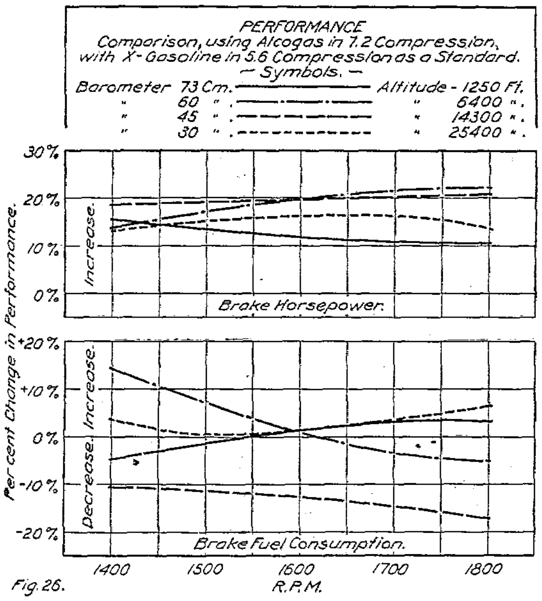
PERFORMANCE
Comparison, using Alcogas in 7.2 Compression, with X-Gasoline in 5.6 Compression as a Standard.
— Symbols. —
Barometer 73 Cm. Altitude - 1250 Ft.
60 " 6400 "
45 " 14300 "
30 " 25400 "
Percent Change in Performance.
Increase.
Brake Horsepower.
Decrease. Increase.
Brake Fuel Consumption.
30%
20%
10%
0%
+20%
+10%
0%
-10%
-20%
1400
1500
1600
1700
1800
R.P.M.

Fig. 26.

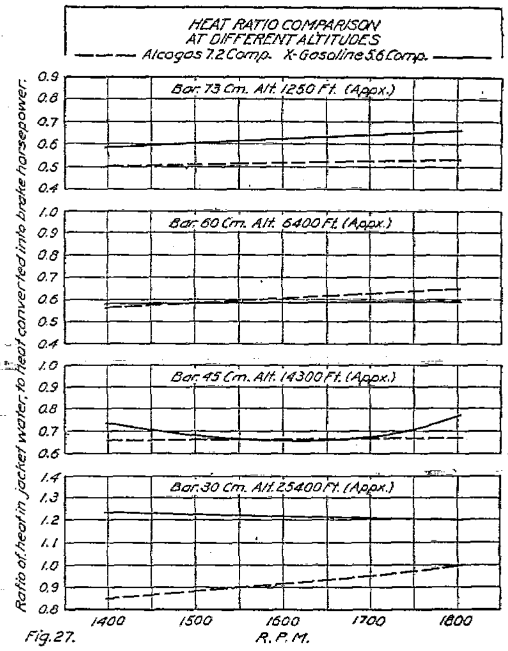
HEAT RATIO COMPARISON AT DIFFERENT ALTITUDES
Alcogas 7.2 Comp. X-Gasoline 5.6 Comp.
Bar. 73 Cm. Alt. 1250 Ft. (Appx.)
Bar. 60 Cm. Alt. 6400 Ft. (Appx.)
Bar. 45 Cm. Alt. 14300 Ft. (Appx.)
Bar. 30 Cm. Alt. 25400 Ft. (Appx.)
Ratio of heat in jacket water, to heat converted into brake horsepower.
1400
1500
1600
1700
1800
R.P.M.

Fig. 27.